Influence of tool geometry on reaction forces and strength of an inseparable joint produced on a prototype stand with the use of jaws

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Abstract. The article describes research on a new and innovative method of producing an inseparable joint and testing its strength. The article shows a new approach in the production of joints with the use of expansion jaws, used as a punch. The tool responds with bending and pressing one part into the other, which results in their permanent connection. In the tests, differentiation was introduced with regard to the height of the applied force to the collar of the connection pipe. A novelty is also a solution based on a complex, parameterized trajectory of the stamp movement consisting of horizontal and vertical displacements. This paper presents the tests of the joints formed at the stand. The article also presents the features of the produced joint by subjecting it to destructive testing: the tensile strength test. The new approach described in this article has resulted in a joint strength increase of approximately 30% using the innovative complex jaw movement of the biaxial clinching process. A joint tensile strength close to 1000N was achieved.

Keywords. Prototype stand, forces, fixed joints, non-detachable tight joints, crimp joints, folded joints, molded joints

1. Introduction

The inseparable connections used in industry for the construction of components of automotive air-conditioning systems, internal combustion engine cooling systems, or the cooling of batteries or heating systems used to power engines and cabs of electric cars require the use of reliable connectors [1], [2] . I determine that it is very necessary to make high-quality joints without defects[3], [4] .

An important aspect is to choose the right method to be used to connect the elements to be joined together. It often depends on the space available for the operation[5], [6]. The joints made by the clinching operation allow for a secure connection of two elements with each other. This method allows the connection of various materials with each other without the risk of corrosion[7]–[9]. This linking uses an operation in which two elements are geometrically combined with partial deformation being caused by a punch and a die [10]–[12] . The presented methods use methods based on 1 step, but also on a two steps, which has been described by the following authors[13] . Another method is the kneading or forcing operation [14]. The advantage of the above-mentioned methods is that the surfaces of the joined materials are not damaged, thus limiting subsequent defects of the final products [15], which affects the economy of the product[16] . Despite of different method of welding aluminum alloy is still difficult to weld, esspecialy thin wall material.[17]–[19] . Currently is know the CMT method of welding or laser welding but is still develop to increse the quality[20] . Other method like friction stir welding can be also alternative [21], adhesive joining or mechanical crimping, clinching[22] . Han et al. [23] was confronting two different methods, Resistance Spot Welding and Self-Pierce Riveting. The main conclusion was that process of mechanically joining parts was more stable than manufacturing inseparable joint with featured welding process. Clinched and crimped joints can be treated as an intermediate solution requiring additional technological operations or final solution. If they are treated as intermediate operations, the following operations should be done: gluing, welding or soldering [24]. The production of inseparable connections involves the necessity to transfer forces or moments to the connected system so it would be able to withstand forces destroying the joint during subsequent technological operations or when using the parts. Salamati et al.[25] investigated various of mechanical joining processes. The fields of this study among others are principles of the processing, applicable materials, process variants, joint mechanical behavior including static and dynamic performance. Weber et al. [26] was confronting different processes for joining by forming of profiles, sheet-,bulk-, and sheet-bulk-components. The study includes the achievable joining mechanisms as well as the significant process parameters influencing these mechanisms. Mori et al.[27] also analyzed joining processes, including cold welding, friction stir welding, self-pierce riveting, mechanical clinching and joining by forming. The comparisons of the processes of joining parts presented in the articles allows to get acquainted with the methods of

joining used in industry as well as their advantages and disadvantages. Briskham et al. [28] investigated best mechanical properties of the joints manufactured by Self-Pierce Riveting, Resistance Spot Welding and Spot Friction Joining. Highest destroying force in studied cases was reached by joint formed by mechanical deformation. Developing methods to increase the strength of the connection through a two-axis complex clinching or crimping movement is a new approach, but the most desirable one, which should be developed for various industries, not only for the automotive and aviation industries. The described method of joining was proposed by Rejek and other authors. They describe the joining of two components, in which the walls are first folded, and then the parts are pressed against each other [29].

After the literature analysis, it was noticed that there were no issues related to clinched connections made by means of a complex jaw movement. It is especially important in cases where it is necessary to apply force in a relatively small space that allows for the proper joint to be made. The solution described in the article below makes it possible to obtain greater connection strength with the use of the same tool and no need to increase access at the site of the jaw attack.

2. Materials and methods

The designed and manufactured tooling is capable of biaxial and parametric production of inseparable joints. It is dedicated to the production of clinched, crimped or bending joints. The connection is made by punches with a die, jaws or cones. The investigated connection case before the manufacturing operation is shown in Fig. 1.a. It consists of a pipe and a connection pipe made of the material 6060, described in tables 1 and 2[30] .

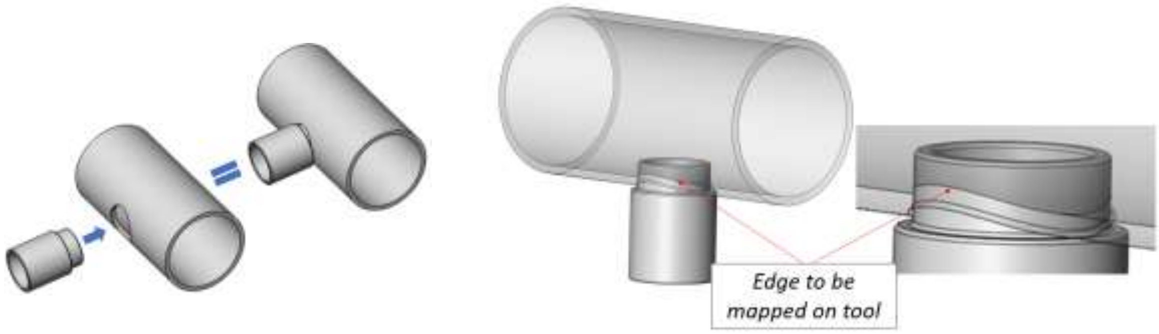
Table 1. Chemical composition of the aluminum alloy 6060 T4 according to the EN-573-3: 1994

Si [%]	Fe [%]	Cu [%]	Mn [%]	Mg [%]	Cr [%]	Zn [%]	Ti [%]	Other		Al. [%]
								Each [%]	Total [%]	
0,30-0,60	0,10-0,30	0,10	0,10	0,35-0,60	0,05	0,15	0,10	0,05	0,15	The rest

Table 2. Mechanical properties of the Aluminum alloy 6060 T4 in accordance with EN 755-2: 2008

Alloy	Temper	Wall thickness [mm]	Tensile strength R_m [MPa]	Yield point $R_{p0,2}$ [MPa]	Elongation		Hardness Brinell HBS
					A50mm % min	A % min	
6060	T4	>25	120	60	14	160	45

The joint has been designed in such a way as to best match both elements with each other. While still maintaining the possibility to be made by a complex two-axis movement of the forming tool. In the described case, the joint will be produced by expansion jaws with a new shape of the forming surface. The lower edge of the tool is mapped above the intersection edge of the pipe and connection pipe shown in (Fig. 2.b).



a) b)

Fig. 1. View of the pipe with a connection pipe:
a) joint components, b) marked edge to be mapped on tool.

In order to manufacture the tested connection between the pipe and the connection pipe, the forming jaws will be moving diverge in four directions for the vertical plane and one in the vertical direction according to the force of gravity. The joined parts during the crimping operation must be pressed down. The resulting joint strength is also dependent on the fit of the parts. Crimping method of the connection is schematically shown in three steps in Fig. 2. In the described case, the jaws were made of Inconel Vascomax C350 martensitic steel. Allowing to achieve high loads. The tools were hardened to 58-60 HRC.

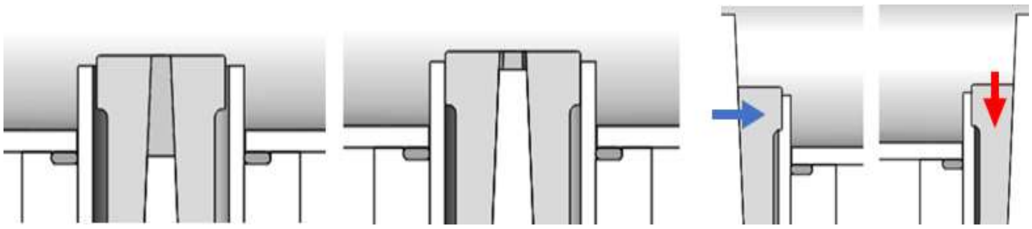


Fig. 2. Theoretical diagram of the joint formation: 1st phase - before the jaws enter (no contact with parts) (a); 2nd phase - contact with parts (b); 3rd phase - jaws entering the material (c); 4th phase vertical movement of the jaws consistent with gravity force.

2.1. **Stand and socket concept**

Designing stands requires an analysis of the functions of the tooling or the machine that it is to fulfill. Concept considerations most often lie between the proper quality of the manufactured joint and the production cost of the machine and joint. A prototype stand was designed for the production of the joint, the design of which was granted a patent number: 426083 (22) 2018 06 26. The joints described previously were made at the stand, which is based on plate-and-column structure. Design of the stand makes it possible to work in two vertical axes at the same time. Each axis is equipped with a servo drive and an external force sensor that monitors the response forces achieved in the production of the joint. The displacements generated by servomotors are measured with an optical encoder mounted in the motor. This solution enables parametric setting of the point where the jaws attack the connection pipe. The zero point is of attacking height of jaws is assumed on the mapping edge between the pipe and the connection pipe. This stand allows for the repeatable production of joints and it is flexible to adapt to parts of various dimensions.

The relatively small area where the desired amount of force or torque should be applied to make the joint gives limited access to the application of wedges to the jaws. Surfaces of wedges are responsible for transmitting the vertical force to the jaw, which moves in the horizontal direction. Achieved transmission ratio in the system is 1:19. Figure 3 shows the view of the station with elements of actors and sensors.

Servo motors from Beckhoff were used as actors. Their nominal torque is 10Nm and the speed of 2300 rpm. The sensory and measurement systems are based on the following elements:

• CL 16m 30kN force sensor with a CL 10D 4-20mA transducer and a resolution of 0.5%,

• CL 21RS 30kN force sensor with CL transducer 10D 4-20mA and 0.5% resolution.

In order to collect the obtained results, a PC computer with a PLC was used. This system allows you to collect 4-20mA current signals from force sensors and two 18-bit optical encoders responsible for tracking jaw displacement. The joint has been manufactured using a specially designed tooling that allows the proper transfer of the necessary forces to the system in order to produce the joint. The tooling is also designed in the concept of biaxial force application. It is possible to control the jaws in the horizontal direction of the X and Y axis and the vertical Z axis for the entire system (Fig.3).

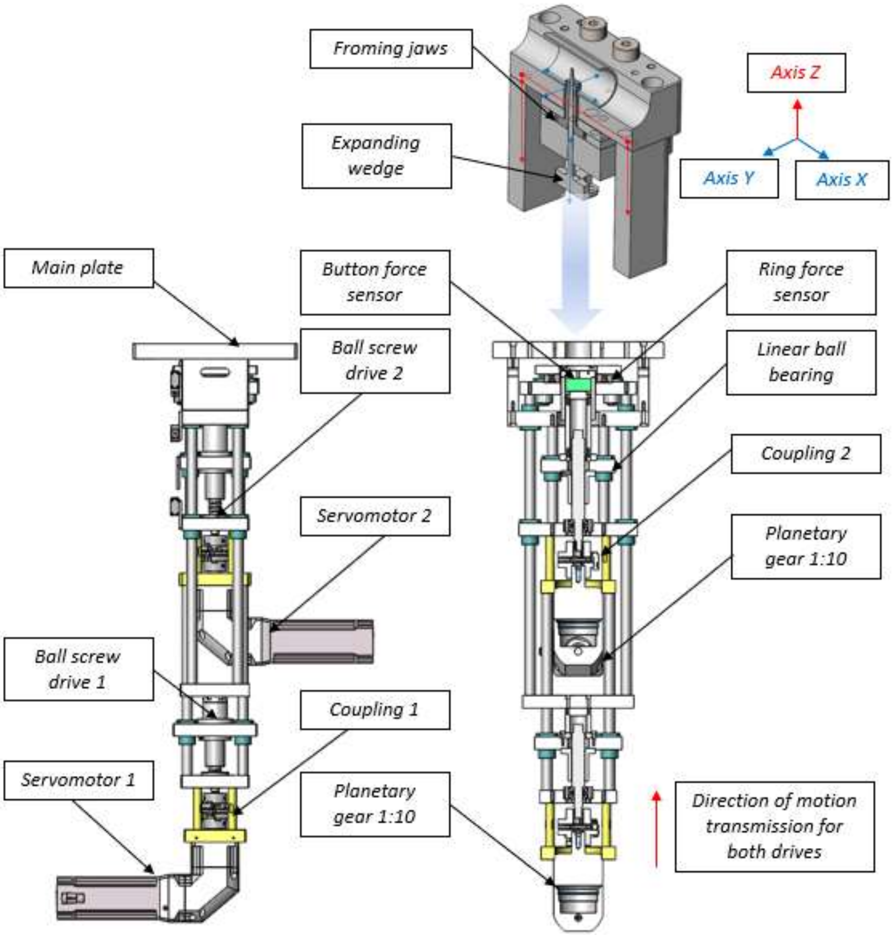


Fig. 3. Stand view used in the production of the joint view of the tooling for making the joint

2.2. Methodology of the experiment

Eighteen sets of parts were produced for the tests. The described experiment was prepared on the basis of samples characterized by one set of diameters. The goal of the research was to find a parameter that gives the greatest effect in the form of tensile strength of the joint. The cross-section of the joint in the 3d view is shown in Figure 4 together with the measurement table in Table 3.

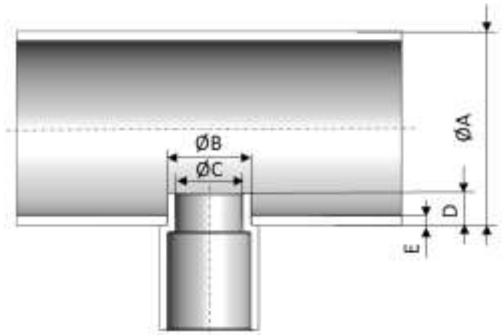


Fig. 4. Joint view with characteristic dimensions.

Table 3. Measurement result of the joint

No	Case	ØA [mm]	ØB [mm]	ØC [mm]	D [mm]	E [mm]
1	A	30 h11	13 H8/h7	10,5	5	1,5

The preparation of the joints was based on a tool in the form of one set of jaws, with a forming surface on which vertical grooves used for crimping were made. The jaws have been divided into two groups, high and low, so as to best reflect the inner edge of the tube opening. The experiment was divided into two main groups of joints, the first criterion is the position of the jaws, which relates to the attacking height of the jaws on the collar of connection pipe noted by "LP" shown in Fig 5. The tests took the height of the jaws attack on the collar marked as two parameters "00" for which the distance LP is 5mm and "+05", where the LP is 5.5mm. This means that the difference in force application was 0.5mm.

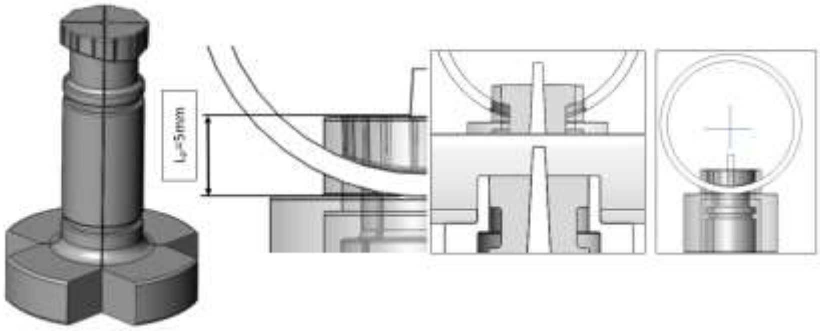


Fig. 5. View of the forming jaws for manufacturing the joint.

Diversification was also made in motion, the joints were made with single movement of the forming jaws, i.e. diverged only horizontally in 4 directions, and with a complex movement, where jaws after the horizontal movement, performed downward working movement of 0.3 mm and 0.5 mm (table 4).

Table 4. Design of experiment.

Parameter „L_P”	„+05”				„00”	
Type of motion	Type of motion				Type of motion	
	1 axis movement	2 axis movement	1 axis movement	2 axis movement	1 axis movement	2 axis movement
Jaws movement value	0,3mm	0,3mm	0,5mm	0,5mm	0,5mm	0,5mm
Vertical movement	N/D	0,1mm	N/D	0,2mm	N/D	0,1mm
Case	1	2	3	4	5	6
Tensile strength test	X	X	X	X	X	X

The joints were made under constant sensor control in the form of a displacement and force sensor. The results are represented by graphs showing the exact reaction forces needed to produce a given joint. Manufactured samples were subjected to tensile strength tests. The strength of the joint was tested on the same stand, based on servomotors and sensors, which was dedicated to monitor joint formation. In order to perform the test, internal threads were made in the connection pipes, while the pipes were gripped by socket with mapped shape of pipe.

3 FEA analysis

The finite element analysis method was performed for all samples presented in Table 4, using Solidworks Simulation software with an addition that allows the testing of materials behaving as a nonlinear. With this type of consideration, it is possible to determine the most advantageous shape of the forming tools without the need for costly and time-consuming tests. Due to the axially symmetrical nature of the sample, an analysis was carried out for its quarter, which allowed to reduce the number of elements to be calculated, and at the same time to increase the accuracy for the tested sample. The material that was used on the analyzed parts was 6060 T4 aluminum, for which a strength graph, shown in Fig. 6, was made and implemented to the program as a model for calculations.

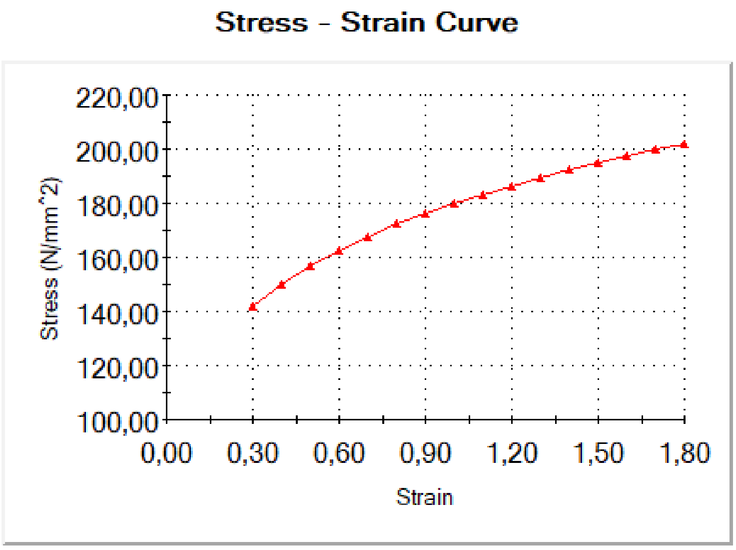


Fig. 6. Stress – Strain Curve for aluminum 6060 T4.

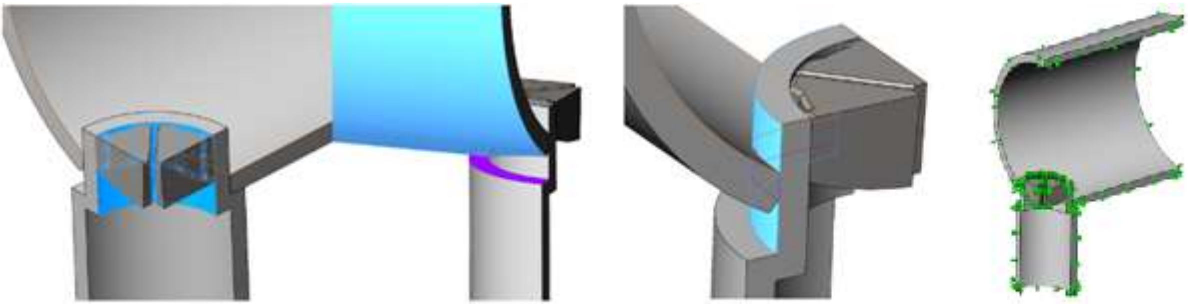
The program automatically retrieves all information from the graph except for the Poisson's ratio which has been set at 0.33. The type of model that has been established for the calculations of these samples is the Von Mises method, which is the best equivalent for this type of test, and the plot itself starts with an assumed yield strength to render the parts non-linear. The program calculates the steps using the formula below:

$$\sigma = \sqrt{0,5 * \left(\left(\sigma_x - \sigma_y\right)^2 - \left(\sigma_y - \sigma_z\right)^2 - (\sigma_z - \sigma_x)^2 \right) + 3 * (\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zy}^2)} \qquad (1)$$

The material for the jaws analyzed in the program is K490, for which the values are given in Table 5, as the jaws themselves are not tested, they were considered rigid so as not to interfere with the results of the analysis. The simulation lasted 1 or 2 seconds, depending on the number of movements. 1s was assumed for a single move. while the double movement was tested for 2s, respectively, the horizontal movement lasted 1s, and then the vertical movement for 1s. The Newton-Raphson iteration method was adopted. The iterations that have been accepted for testing are shown in Fig. 7.a, Fig. 7.b and Fig. 7.c, they describe the possible contact between the parts of the assembly. The degrees of freedom in the space of the test samples were also limited according to the actual test (Fig. 7.d). The friction coefficient was set at 0.05.

Table 5. Properties of the K490 material, used for jaws.

Properties of steel K490					
Chemical composition					
C [%]	Cr [%]	Mo [%]	V [%]	W [%]	Nb [%]
1,4	6,4	1,5	3,7	3,5	+
Mechanical properties					
Young modulus [Mpa]	Density [kg/m3]	Poisson modulus	Tensile Strenght [Mpa]	Yield Point [Mpa]	Specific heat capacity [J/kg*K]
223000	7790	0,28	2436	2098	450



a) b) c) d)

Fig. 7. Fixing in space and contact interactions of the FEM model:
a), b) c) contact iterations, d) considered degrees of freedom

The data of the mesh and the mesh plotted on the model was divided are shown in Fig. 8. According to which the model was divided into a mesh of 1.5 mm, with compaction in the area of the deformed part of 0.5 mm. In this way, 10,540 elements were the subject of the analysis.

Mesh type	Solid mesh
Mesh used	Standard mesh
Automatic Transition	Off
Include Mesh auto loops	Off
Jacobian points	16 points
Element size	1.5 mm
Tolerance	0.066
Mesh quality	High
Total nodes	18816
Total elements	10540
Mesh control	Defined

Fig. 8. Mesh on the analysis parts and properties of the mesh during FEA.

The results for all analyzes are presented in Table 7. The presented results are in line with the expectations and correspond to the implemented displacement, hence it can be assumed that the analysis was carried out correctly. Fig 9 shows how the sample will behave after reaching the assumed displacement, and where the greatest stresses are to be expected, and thus the forces necessary for the desired deformation. Thanks to the analysis carried out in this way, it is easy to determine the most advantageous shape of the tool, to determine to which values the increase in displacement does not damage the sample.

Table 7. Result of analysed samples

Parameter "Lp"	"+05"				"00"	
Case	1	2	3	4	5	6
MaxVon Mises Stress [MPa]	60,827	68,793	96,047	108,946	162,881	165,348

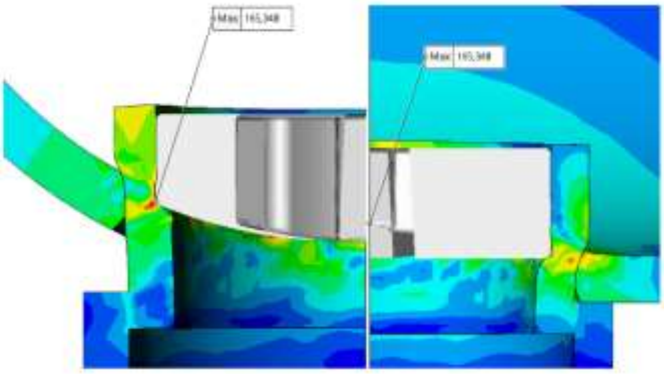
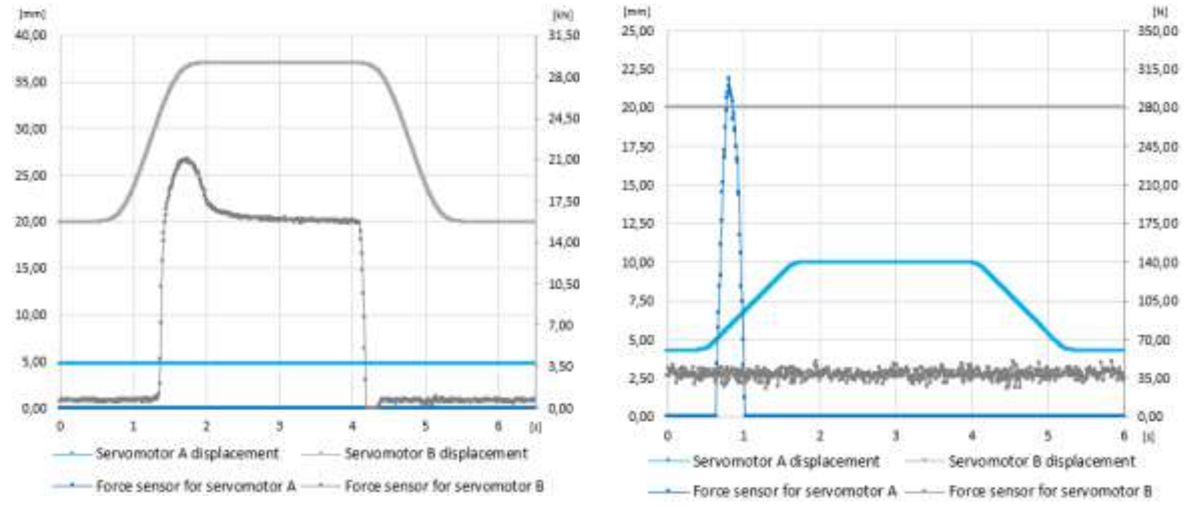


Fig. 9. Visualisation of deformation on Solidworks.

4. Results and discussion

The research was based on analysis of two different methods of producing a joint with different values of parameters characterizing a given method of joint production. In all analyzed cases, the same type of forming jaws were used to produce a fixed connection of two parts.

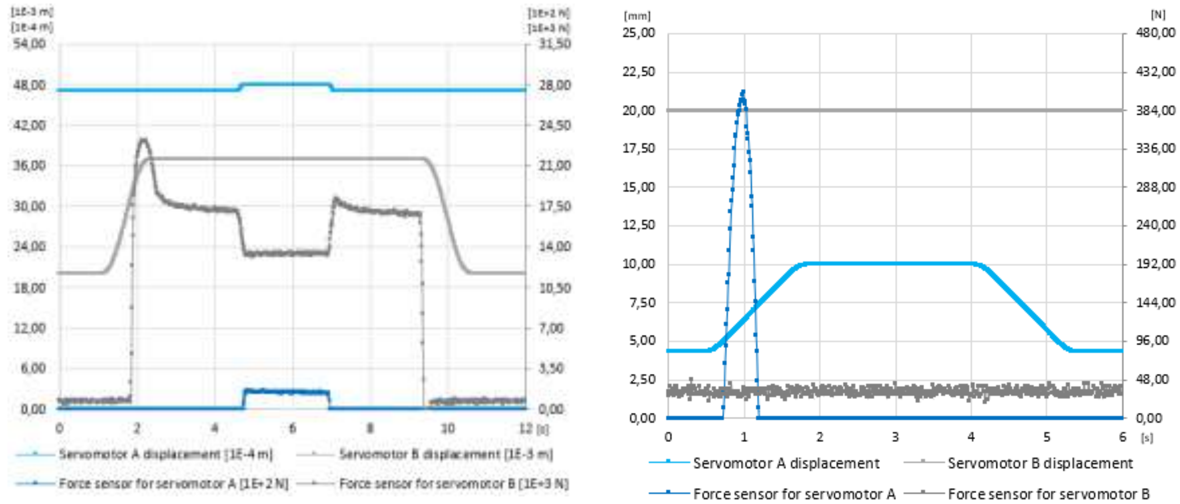
In first case, the parameter defining the height of the force application took the value of 5.5 mm and was defined as "+05". On the other hand, the parameter characterizing the jaws movement was 0.3 mm. The speed of movement in the radial direction was 1.83 mm / s. The reaction forces recorded on the sensor in form of flat cylinder reached a maximum value in the direction of the vertical axis of 1.1 kN. After conversion to radial movement, this value was 21.05 kN for a total of 4 jaws (Fig. 10.a). The strength of the tested joint was 307N, the value occurred after destruction of the joint (Fig. 10.b).



a) b)

Fig. 10. Obtained data for joint produced by jaws with single movement, height LP "+05", movements of forming jaws 0.3mm: a) Values of the reaction forces, b) the strength of the joint in the tensile test,

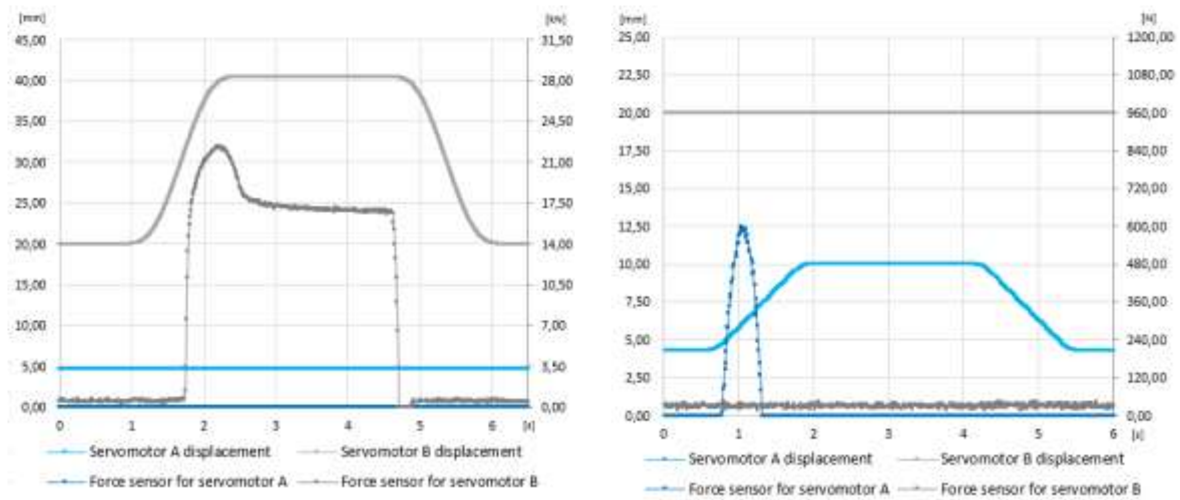
The second analyzed case was manufactured with complex motion, divided into two stages. In the first phase, and then vertical movement was 0.1 mm downwards at a speed of 35 mm / s. Second displacement was done to additionally form the material and increase the strength of the joint. The first stage of force increase was slightly higher, as for the group described previously, has reached value of 23.24 kN. For the second stage a decrease in force was observed, which can be connected with the beginning of vertical movement and increase of force for the ring sensor (Fig. 11.a). Manufacturing the joint by a complex movement allowed to increase the strength. The connection of two parts was destroyed at the value of 408 N (Fig. 11.b).



a) b)

Fig. 11. Obtained data for joint produced by jaws with single movement, height LP "+05", movements of forming jaws 0.3mm and vertical movement 0.1mm: a) Values of the reaction forces, b) the strength of the joint in the tensile test,

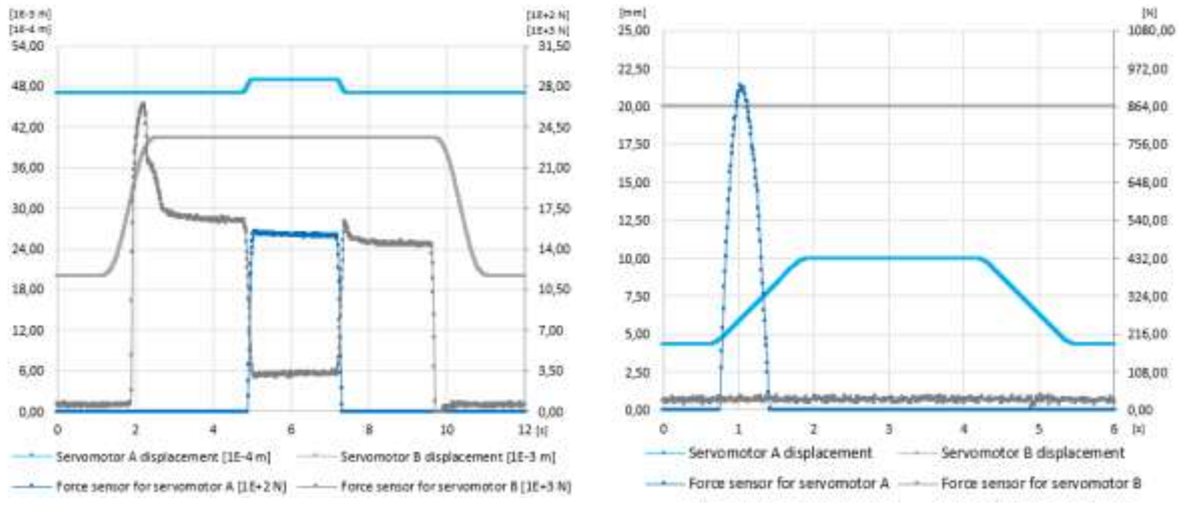
The third analyzed case concerned a joint made with a single movement with the parameter defining the height of the force applied by the value of 5.5 mm, defined as "+05". Radial movement of the jaws was 0.5 mm per side. The speed of movement in the radial direction was 1.83 mm / s. The reaction forces registered on the sensor reached the maximum value in the direction of the vertical axis, equal to 1.17 kN. After conversion to radial movement, this value was 22.41 kN for a total of 4 jaws (Fig 12.a). The strength of the tested joint for this case reached value of 599 N, the higher force has destroyed joint (Fig. 12.b).



a) b)

Fig. 12. Obtained data for joint produced by jaws with single movement, height LP "+05", movements of forming jaws 0.5mm: a) Values of the reaction forces, b) the strength of the joint in the tensile test,

In the fourth case, the joint produced with the parameter determining the height of the force applied by a value of 5.5 mm, defined as "+05", and the parameter characterizing the distance of the jaws by the value of 0.5 mm, was tested using complex motion. In the second phase of the movement, the jaws made a vertical movement of 0.2 mm downwards at a speed of 35 mm / s. The first stage of force increase was higher than for the group described previously, as it amounted to 26.50 kN, then a decrease in force was observed, denoting the beginning of vertical movement, and its increase for the ring sensor installed in the external system (Fig. 13.a). Performing the compound movement allowed to increase the strength of the joint, as it failed to deteriorate until the value of 925 N (Fig. 13.b).

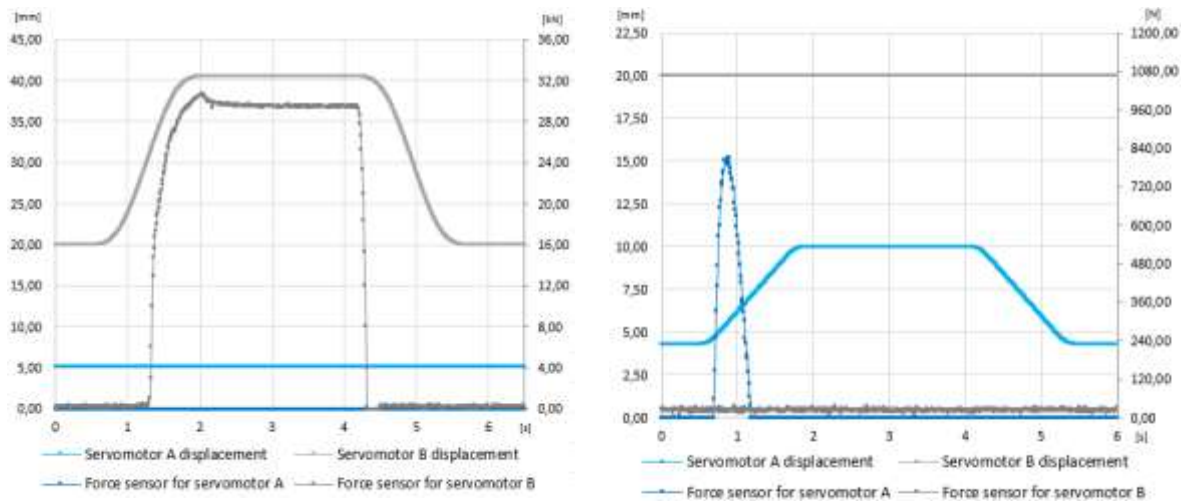


a) b)

Fig. 13. Obtained data for joint produced by jaws with single movement, height LP "+05", movements of forming jaws 0.5mm and vertical movement 0.2mm: a) Values of the reaction forces, b) the strength of the joint in the tensile test,

The fifth analyzed case concerned a joint made with a straight movement with the parameter specifying the height of the force application of 5.0 mm, defined as "+00". On

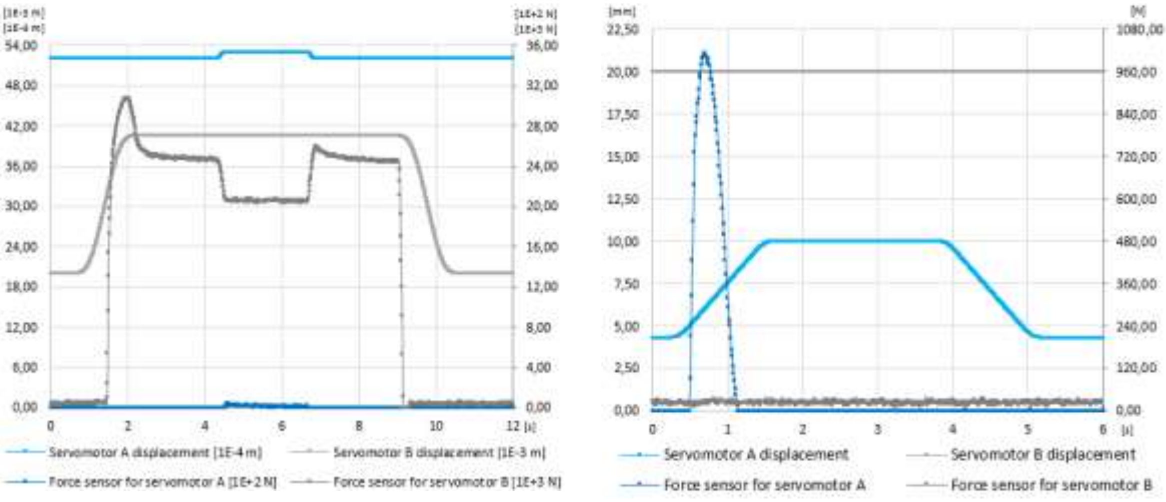
the other hand, the parameter characterizing the distance between the jaws spreading was 0.5mm. The speed of movement in the radial direction was 1.83 mm / s. The reaction forces recorded on the "button" sensor reached the maximum value in the direction of the vertical axis, equal to 1.60 kN. After conversion to radial movement, the value was 30.67 kN for a total of 4 jaws (Fig. 14.a). With regard to the strength of the tested joint, its complete failure occurred for the value of 810 N (Fig. 14.b).



a) b)

Fig. 14. Obtained data for joint produced by jaws with single movement, height LP "+00", movements of forming jaws 0.5mm: a) Values of the reaction forces, b) the strength of the joint in the tensile test,

The last case concerned a joint produced with the parameter defining the height of the force applied by the value of 5.0 mm, ie "+00", and the parameter characterizing the distance of the jaws spread by the value of 0.5 mm, using compound motion. In the second phase of the movement, the jaws made a vertical movement of 0.1 mm downwards at a speed of 35 mm / s. The first stage of increasing the force was similar to the group described previously, as it amounted to 30.79 kN, then a decrease in the force was observed, denoting the beginning of vertical movement, and its increase for the ring sensor installed in the external system (Fig. 15.a). Completed motion allowed to increase the strength of the joint, as it failed to deteriorate until the value of 1014 N (Fig. 15.b).



a) b)

Fig. 15. Obtained data for joint produced by jaws with single movement, height LP "+00", movements of forming jaws 0.5mm and vertical movement 0.1mm: a) Values of the reaction forces, b) the strength of the joint in the tensile test.

By summarizing the values of the resultant reaction forces and the strength of joints produced with the same spreading jaws with the use of different parameters characterizing the given method of making the joint, the impact of the amount of force applied to the system on the occurring reaction forces and joint strength was found. For the first case, where the joint was produced by the basic method, the lowest value of reaction forces was observed, however, the joint strength was also the lowest among the tested cases. For the second case, with a 10% increase in the reaction forces and the application of the method with complex movement of expanding jaws, a 33% increase in the strength of the joint was noted. During further tests, the parameter characterizing the jaw spreading distance was increased from 0.3 mm to 0.5 mm, which in the case of straight jaw movement resulted in an increase in reaction forces by 6% compared to the first case and an increase in the joint strength by 95% compared to the first case. The fourth case concerned the use of the method of complex movement of expanding jaws with the parameters characterizing the jaw opening path of 0.5 mm for horizontal movement and 0.2 mm for vertical movement, thus there was an 18% increase in reaction forces and a 54% increase in joint strength compared to the third case . Relating the obtained data to the first case, a 26% increase in reaction forces was observed with a simultaneous 201% increase in joint strength. In subsequent cases, the influence of the LP parameter on the reaction forces during the production of the joint and the strength of the joint were

investigated. Compared to the previous cases, the height of the force application was changed from 5.5 mm to 5.0 mm, which resulted in a straight movement increase of the reaction forces by 37% and the joint strength by 35% compared to the third case. Relative to the base case, the reaction forces increased by 46%, but the joint strength increased by 264%. On the other hand, in the case of complex motion with the LP parameter equal to "00", the height of the application of forces equal to 5.0 mm and vertical motion of 0.1 mm, an increase in reaction forces by 16% and joint strength by 10% was observed compared to the fourth case. In relation to the first case, the reaction forces increased by 46% and the joint strength by 230%. The obtained research results are presented in Table 8.

Table 8. Comparison of the obtained reaction forces during the production of the joint and strength of joints in a tensile test depending on the process parameters.

Case	LP "+0,5"; s_{jh}=0,3; s_{jv}=0;	LP "+0,5"; s_{jh} =0,3; s_{jv}=0,1;	LP "+0,5"; s_{jh} =0,5; s_{jv}=0;	LP "+0,5"; s_{jh} =0,5; s_{jv} =0,2;	LP "+0,0"; s_{jh} =0,5; s_{jv}=0;	LP "+0,0"; s_{jh} =0,5; s_{jv} =0,1;
Reaction forces during the production of the joint [kN]	21,1	23,2	22,4	26,5	30,7	30,8
Strength of joints in a tensile test [kN]	0,3	0,4	0,6	0,9	0,8	1,0

The analyzes show that the strength and reaction forces needed to produce the joint are influenced by the distance LP, which affects the angle formed between the flange wall of the rivet and the inner edge of the hole in the pipe. In fixed joints, there is a division according to the purpose of their implementation. The first group is for indirect connections, while the second group is for final connections. A distinction in the division is made due to the necessity to perform further operations in order for the combination of elements to meet the expected requirements. The presented diagrams make it possible to track the formation of a joint and to fully control its formation. The results obtained by simulating in Solidworks are reflected in the data recorded during the actual test. The discrepancies that can be seen when comparing the two graphs may result from the absorption of forces by the jaws and intermediate parts due to their deformation. These parts are not taken into account in the FEA analysis, which may cause some differences.

However, simulation effectively allows a full preview of the deformations that are reflected in reality.

6. Conclusions

The conducted analyzes and tests allowed to present a new method of making joints based on the complex movement of the jaws as the right way to increase their strength. of the described product. The performed tests and studies allowed for the formulation of the following conclusions:

1. The difference in the height of the force application point between the inflection point and the jaw attack point differs by 0.5 mm, which is 10% of the difference in relation to the Lp parameter. The energy consumption of the joint forming force for case 1 was lower by 10% than for case 2 using composite motion. The joint 2 produced by the movement of the jaws along two axes made it possible to increase the strength of the joint by 33% compared to case 1, giving a force above 400N.

2. The ratio of the joint strength to the required forces to produce it in case 1 and 2 was only 1% higher for the complex motion. The energy consumption of the joint forming force for case 4 was greater by over 18% than for case 3 using composite motion. The joint 4 produced by the movement of the jaws along two axes made it possible to increase the strength of the joint by more than 50% compared to case 5, giving a force over 920N.

3. The ratio of the joint strength to the forces needed to produce it in case 3 and 4 was 3% for both tests. The energy consumption of the joint forming force for case 5 was lower by 1% than for case 6 using complex motion. Which proves that at a low value of the Lp parameter, jaws may slip when moving vertically.

4. The joints 6 produced on the basis of the movement of the jaws in two axes made it possible to increase the strength of the joint by 25% compared to case 5, giving a force above 1000N. The ratio of the joint strength to the forces needed to produce it in case 5 and 6 was 3% for both tests.

5. The greatest strength of the joint was achieved for case 6, however the percentage increase in force was achieved for case 4 which was more than 50% compared to case 3. The machine is equipped with 2 servo systems and external force and displacement measuring systems, giving full possibility of process control. Finite element analysis in Solidworks Simulation can be effectively used to compare the method or shape of forming tools.

6. When comparing the reaction force graph from the actual test to the test carried out with FEA, you can see the reflection of the results.

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